SILVRCLAW III – Advanced Wheel Design and Testing

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Abstract—Enhancing robotic[1,2] surface mobility systems are a fundamental Mars Exploration Program goal because many surface-investigation goals require traversing significant distances in widely varying terrain conditions. SILVRCLAW (Stowable, Inflatable, Large, Vectran, Rigidizable, Cold-resistant, Lightweight, All-terrain Wheel) is an inflatable, rigidizable wheel technology that enables compact robotic vehicles to be deployed with significant ground clearance. Such a vehicle could traverse aggressive rocky terrains with a resultant low obstacle density (less than one obstacle per ~100m), travel over chasms with >1m separation, and offer the mission operator the ability to navigate with orbital-imaging resolution (i.e. with Mars Reconnaissance Orbiter's Highrise telescope). Because of its high intrinsic mobility, SILVRCLAW can negotiate substantial obstacles, thus allowing a robotic rover to climb over obstacles as opposed to driving around them. Such capability could dramatically increase terrain access and rover range for a given weight class. In previous work, we reported on the development and initial testing of a SILVRCLAW exoskeleton wheel shell for purposes of understanding mobility performance and wear in Mars-like simulants. In this work we discuss environmental testbed results of a new cleated SILVRCLAW exoskeleton shell and the current development of a prototype deployable SILVRCLAW.

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1. Introduction

The Mars Exploration Rover (MER) mission has been an ongoing success and has demonstrated an evolutionary step in extraterrestrial mobility systems by traversing >9 km per rover on a distant planet in its current 2.7 year operational life. The MER environments have been in notably low obstacle density, relatively smooth terrains chosen predominantly due to landing system constraints [1]. In the not too distant future, Mars and lunar exploration will likely be extended into higher rock density, steeper slope, segmented terrains associated with sedimentary features on cut slopes on Mars, mountainous and heavily cratered regions, outflow features on Mars, large sand dune-like environments and fractured polar ice cap regions (Mars only). One way to provide access into these new exploration environments is to enhance vehicle wheel ground clearance much like is done in earth analog environments.

The focus of this research work is to ultimately allow relatively small, high density landing packages to achieve required ground clearance through the deployment of an inflatable/rigidizable composite all-terrain wheel that we have coined SILVRCLAW (Fig. 1). In its undeployed state,

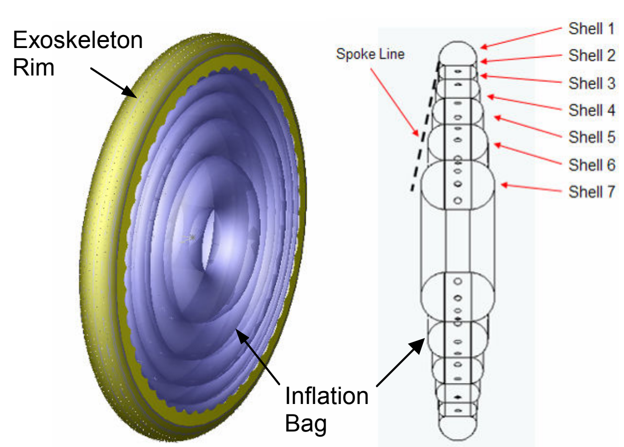

Figure 1 – SILVRCLAW Exoskeleton Rim and Inflation Bag.

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the SILVRCLAW exoskeleton wheel rim and fibrous spoke network are densely packaged somewhat analogous to a parachute. Through the use of gas pressure 34-69 kPa typically (4.9-10 psi), the wheel is deployed, and the fibrous spoke network is pre-strained in tension. The low temperature (brittle transition temperature −70°C) composite exoskeleton rim is rigidized in 10's minutes through the application of heat in an embedded wire heating system. The gas pressure is subsequently released, and the structure is allowed to settle into a new pre-stressed configuration.

In our previous work we have derived a requirement for a 1.3 to 1.5m diameter SILVRCLAW based on mean free paths in Mars Viking rock distributions and the ability to have sufficient ground clearance such that existing orbital imaging resolutions can resolve vehicle hazards [2,3]. These wheel diameters will likely also be required for traversing negative obstacles (i.e. gaps) greater than 1m in segmented terrains. We had also developed a preliminary concept vehicle design for allowing wheel deployment as described above with no ground load (Fig. 2).

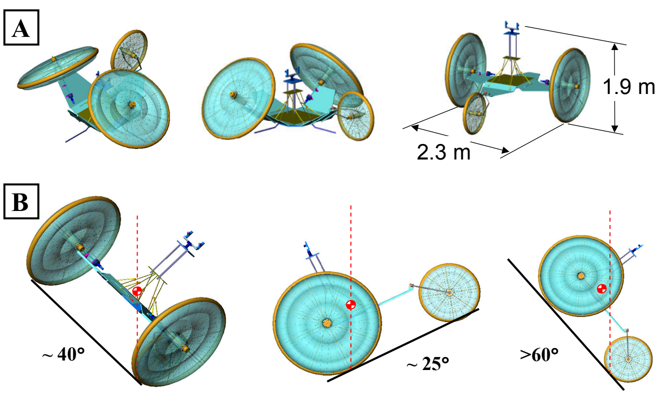

Figure 2 – Concept wheel deployment for a three-wheel rover. A) Wheel deployment; B) Vehicle static stability

In our ongoing work we have developed the following preliminary set of SILVRCLAW performance objectives: 1) Support 100's kg in Mars gravity (Mekg), 2) Mass out at ~10 kg per SILVRCLAW wheel, 3) Climb >60 cm worst case orthogonal obstacles, 4) Traverse >1m gaps, 5) Climb angle of repose slopes (30 degrees on Mars), 6) Maintain a ground contact pressure of <10 kPa for minimal wheel sinkage in low cohesive material, 7) Consume <100 Whr/km per wheel in analog terrains, 8) Endure >100 km in abrasive (basaltic sand and rock) terrains, and 9) Pre-package within 1/20 volume of deployed state.

A preliminary rim exoskeleton (section 2) had been developed and since upgraded with a new cleated tread design in order to 1) evaluate mobility performance characteristics in a custom environmental testbed (section 3) and 2) define wheel configuration for deployment requirements. In the following sections, we report on our recent experimental development progress and test results of the SILVRCLAW prototype wheel development effort.

2. SILVRCLAW Exoskeleton Wheel

In our prior work, we fabricated a SILVRCLAW exoskeleton wheel rim (without deployment bag) based on a design for accommodating impact loads from 1m falls in a Mars gravity field. A summary of environmental test results of this rim is provided in section 3. In general the first SILVRCLAW prototype met the sinkage, traverse energy, in-soil slope climbing, and initial in-soil wear testing objectives defined in section 1. This initial prototype however had insufficient interface contact friction to permit climbing orthogonal obstacles greater than ~20 cm.

To address contact friction for obstacle climbing, an investigation into a cleated wheel surface was undertaken to understand optimal cleat geometry and spacing to allow extreme obstacle traversing. A cleat mounting array was integrated into a ½ section of the existing wheel rim (Fig. 3). The cleat mounts permitted replacing and testing various cleat geometries under a loaded wheel in orthogonal rock climbs. A preliminary spiked cleat was chosen that allowed sufficient contact for a worst case 75 cm (wheel radius) orthogonal climb under a 101 Mekg (Mars equivalent kg) with a single cleat in contact with the test obstacles (inverted cylindrical aluminum container and concrete cinder block) without cleat failure. Subsequent to obstacle climb testing, the cleated tread was qualitatively discovered to reduce wheel wear in rocky environments by essentially limiting relative wheel slip and direct contact between the composite rim and abrasive rock surfaces (Fig. 6).

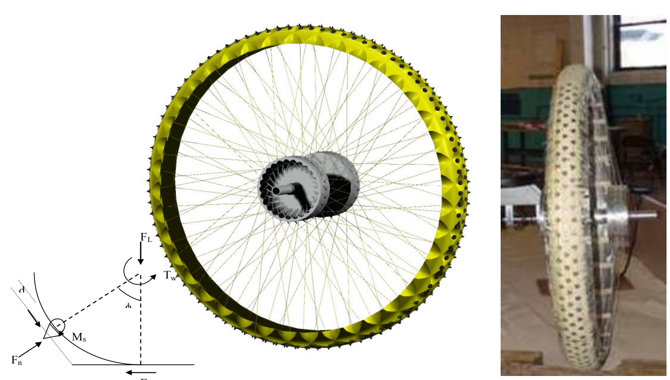

Figure 3 – Cleated SILVRCLAW Exoskeleton.

3. SILVRCLAW EXOSKELETON WHEEL RIM ENVIRONMENTAL TESTING

Upgraded Wheel Testbed Hardware

A detailed description of the original environmental testbed developed for SILVRCLAW testing is provided in [3]. During extreme obstacle climbing with cleats, significant wheel side-loading was noted due to the fixed radial constraint of the testbed arm relative to the intended direction of travel of the wheel. While the wheel is designed to take significant side loads (originally worst case loads associated with lifting a rover as shown in Figure 2), the suspension system connecting to the wheel hub ideally has some axial compliance to mitigate wheel side-loading. To study this effect as well as support future development of an optimal SILVRCLAW rover suspension system, an extra actuated degree of freedom was incorporated into the testbed radial arm as shown in Fig. 4.

All degrees of freedom shown in Fig. 4 are instrumented. Encoders measure the relative position of the vertical actuator, the relative angle of the central pivot, and the relative angle of the wheel. Homing to a limit switch on the telescopic actuator makes later encoder readings absolute. A potentiometer measures the absolute angle of the elbow joint. A torque sensor is placed on the output of the wheel's drivetrain. The wheel motor shaft is connected to a gearbox and then a harmonic drive. The torque sensor is coupled to the harmonic drive output.

Control and Data Logging

The testbed is controlled by two motion controller units and one PC. The motion controllers are DMC-1425 units from Galil Motion Control. These devices carry out closed-loop, PID control of the three actuators in the system, report encoder readings, and sample analog sensors such as the elbow joint potentiometer and the torque sensor. The motion controllers share an Ethernet segment, and a HomePlug power-line bridge connects the PC to this segment through a slip ring on the central pivot joint. A full packet of all testbed sensor data can be logged by the PC at a rate of approximately 50 Hz. Faster frequencies can be achieved by sampling fewer data.

Soils and Obstacles

The walls of the testbed's circular track are approximately 60 cm high, so a variety of soils, obstacles, and slopes can be used (Fig. 5,6). Throughout our work we have used three types of soils:

- **Fine silica sand (original testbed simulant):** its geophysical properties are similar to those of Martian soils as estimated from data collected by the Viking and Pathfinder robots. We use a mix of fine silica sands with cohesion of 1 to 2 kPa (.15 to .3 psi) and internal friction of 28 to 32 degrees. These are good values for simulating top-layer Martian soils.

- **MARS2 simulant:** consists of cinder fines supplied by Select Resources from the Boron Mine outside Bakersfield, California. This red-colored formula features fines less than 200 microns in size and is being tested by planetary scientists at JPL to simulate the Mars bulk soil [4,5].

- **Crushed basalt:** consists of shattered basaltic clasts from 1.5 mm to 2.5 cm in size. This simulates a meteoric spread surface rock layer. It is placed on top of the MARS2 simulant over a ¼ section of the testbed.

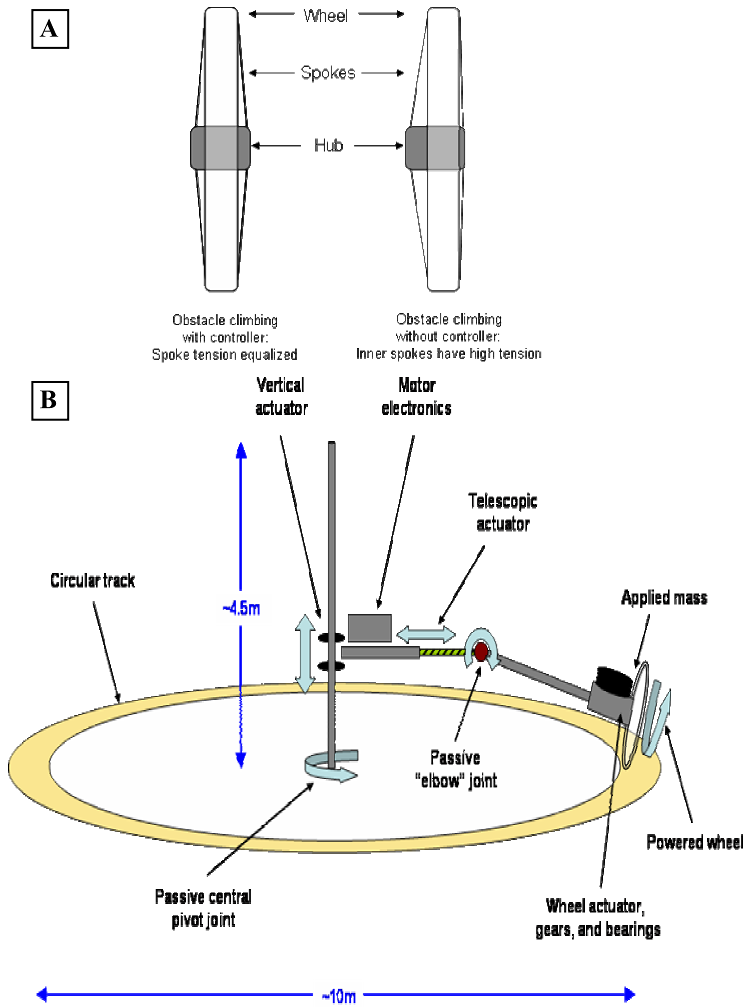

Figure 4. Upgraded Testbed. A) Exaggerated wheel side-loading; B) Adapted SILVRCLAW testbed configuration - two actuated degrees of freedom and two passive degrees of freedom to propel the SILVRCLAW wheel through a circular track while minimizing side loading.

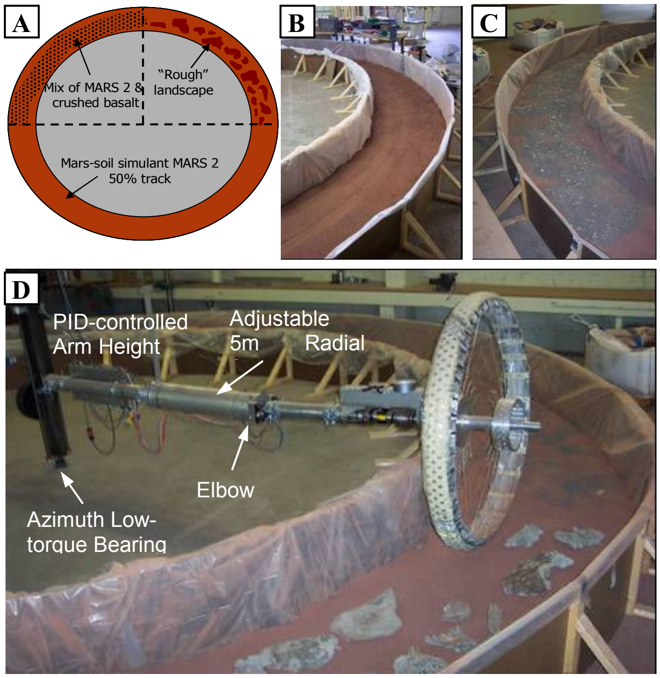

Figure 5 – Upgraded 10m Diameter Testbed Environment. A) Terrain ¼ sections; B) JPL MARS2 simulant; C) JPL MARS2 simulant with shattered basaltic clast surface coverage; D) Simulated Mars Viking vessicular basaltic rock distribution.

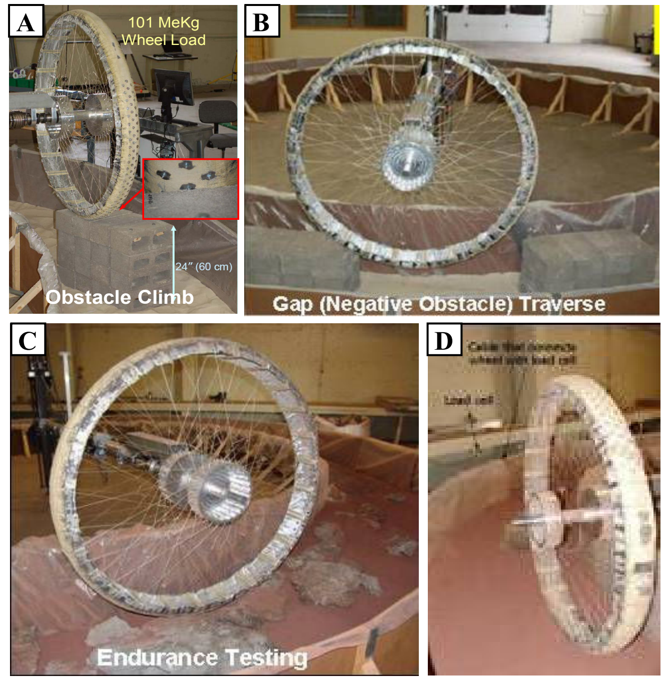

Figure 6 – Cleated SILVRCLAW exoskeleton environmental testing overview. A) Extreme obstacle climbing (60cm shown); B) 1.2m Gap Traverse; C) Endurance testing in Viking rock distribution; D) Drawbar pull tests;

We have also placed three types of obstacles in the track:

- **Cinder blocks:** discrete, step-shaped, rough obstacles for climbing and gap-crossing tests.
- **Basalt boulders:** vessiclar, basaltic boulders selected to mimic the size distribution, hardness, and roughness of Mars ranging from 15 to 60 cm in size currently covering ¼ section of the testbed.
- **Mounds of MARS2 simulant:** the MARS2 simulant can be piled into mounds of varying slope, up to around 30 degrees.

Exoskeleton Wheel Rim Testing

Previous environmental testing of the prototype exoskeleton rim shell in the course silica sand demonstrated sinkage values of 1.8-2.6 cm under 101-184 Mekg load respectively, low traverse energy consumption of 10's Whr/km (Table 1), and sufficient skin friction to permit 31 degree slope climbs based on drawbar pull tests [3]. In general all of these values improved across the board in the MARS2 simulant with no obstacles. Static wheel sinkage dropped to several mm with an elliptic footprint of 7 cm x 15 cm (semi-minor x semi-major axes respectively) with a ground pressure of ~50 kPa.

Table 1. Summary of SILVRCLAW wheel performance in abrasive silica sand testbed.

Average Power Dissipated in Soil Work * All Values for Ground Speed of 3.7 cm/s (130 m/hr)		
Mars Equivalent Wheel Loading (kg)	Power (W)	Energy Consumption (Whr/km)
101.8	1.40	10.8
128.7	1.75	13.5
136.3	1.85	14.2
157.2	2.25	17.3
166.9	2.35	18.1

As expected, power and wheel torque numbers increased in the presence of obstacles. Table 2 summarizes the power and torque values running the exoskeleton rim with 101 Mekg in the updated testbed. Energy consumption remained at <50 Whr/km.

Table 2. Summary of SILVRCLAW wheel performance in updated testbed

Maximum Power and Torque for Various Speed Runs							
Obstacle	Figure Letter	Power (W) 3 cm/s	Torque (N-m) 3 cm/s	Power (W) 6 cm/s	Torque (N-m) 6 cm/s	Power (W) 9 cm/s	Torque (N-m) 9 cm/s
20 cm Boulder	A	9	230	-	-	-	-
30 cm Mound	B	7	180	-	-	-	-
MARS2	C	2-3	40-70	3-3.5	40-45	5-6	40-50
MARS2 + Crushed Basalt	D	2-3	45-80	4-4.5	50-55	4.5-7	40-55
Basalt Boulder Patch	E	7	180	15	190	22-25	190-210

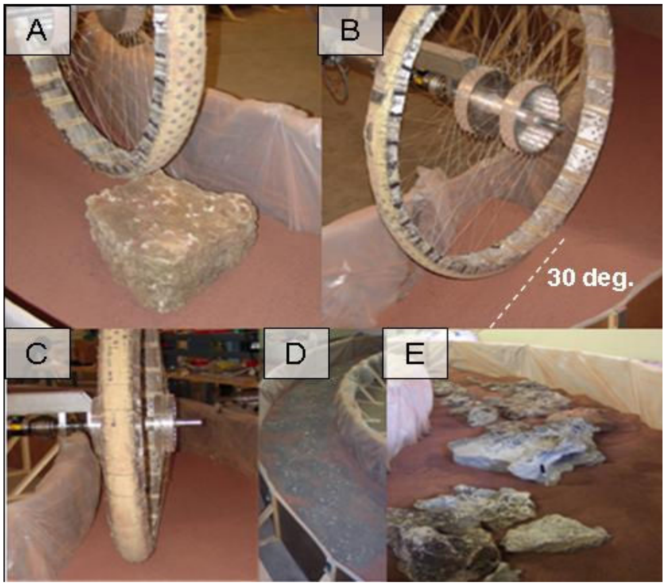

Figure 7. SILVRCLAW testing conditions summarized in Table 2. A) 20 cm boulder; B) 30 cm mound; C) MARS2; D) MARS2 + crushed basalt; E) Basalt boulder patch

Endurance Testing and Test Bed Statistic Summaries

To date, the SILVRCLAW exoskeleton shown in Figures 5,6 has completed ~85km of traversing in abrasive soils and rocky terrains (~71km of endurance runs in abrasive silica sands, 7km of endurance runs in upgraded testbed with basaltic sands, basaltic clasts, and basalt rock distribution, and ~6km of additional testing in abrasive silica sands). Figure 7 illustrates recent wear performance on cleated and uncleated portions of the exoskeleton wheel rim in the upgraded testbed starting after the ~77km in the initial silica sand testbed. Because the cleats themselves saw a substantial portion of the external loading, the wear rates in the cleated sections were observed to be less than the non-cleated sections Table 3 summarizes the endurance runs and Table 4 summarizes the overall testbed statistics of the exoskeleton wheel rim.

Table 3. SILVRCLAW exoskeleton endurance statistics.

Endurance Testing Summary			
Soil	**Duration (hours)**	**Speed (cm/s)**	**Distance (km)**
Silica Sand	21.0	14.4	11.0
Silica Sand	24.0	28.8	25.0
MARS2, crushed basalt, basalt boulders	34.0	28.8	35.0
MARS2, crushed basalt, basalt boulders	42.3	2.9	4.5
MARS2, crushed basalt, basalt boulders	24.0	2.9	2.5

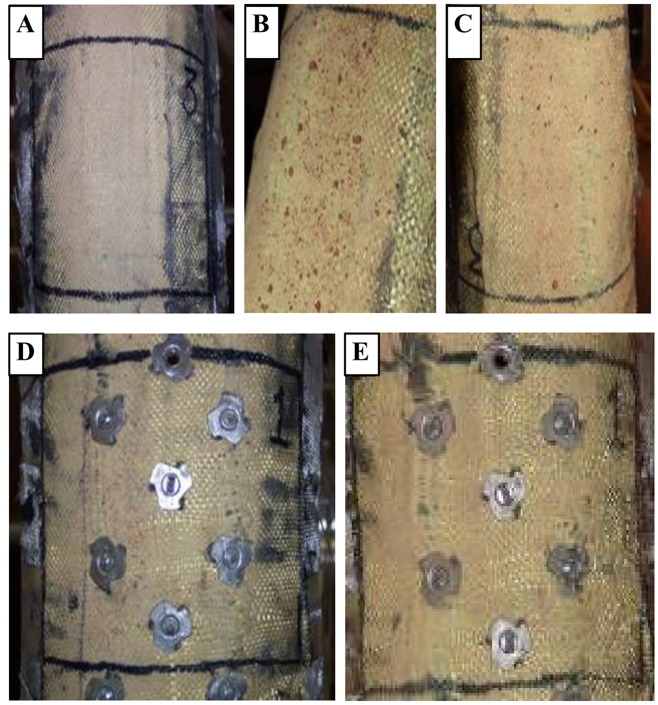

Figure 8 – SILVRCLAW endurance test results starting at ~77km in silica sands + X km in upgraded testbed. A) X = +0km uncleated; B) X = +3.5km uncleated; C) X = +7km uncleated rim; D) X = +0km cleated; E) X = +7 km cleated.

Table 4. SILVRCLAW exoskeleton rim testbed statistics.

Test Bed Statistics Summary
• **60 sets of Mobility Experiments:**
– In-soil Mobility
– Drawbar Pull
– Orthogonal Obstacle Climbing
– Orthogonal Gap Crossing
– Weak Soil Slope Climbing
– Static Sinkage
– Combined Terrain Negotiation
• **4 Major Endurance Run (all with nominal wheel loading ~40kg):**
– 1st Run: 11.11 km in 21 hours (no interruptions)
– 2nd Run: 24 km in 2 hours (no interruptions)
– 3rd Run: 34 km in 34 hours (3 data logging resets; no wheel problems)
– 4th Run: 7 km in 66 hours (endurance tests in MARS2, crushed basalt, and boulders)
• **Min Speed: 3.68 cm/sec, Max Speed: 58.9 cm/sec**
• **Min Wheel Loading: 40 kg, Max Wheel Loading: 70 kg (101 – 185 Mars eq. kg)**
• **Longest Continuous Run: 34 km (34 hours @ 0.297 m/sec; 10/06/05 to 10/07/05)**
• **Total Accumulated Distance: ~ 85 km**
• **Total Accumulated Time of Operations: ~140 hours**
• **Recorded Failures: Data Logging Faults**

4. Deployable SILVRCLAW

Rim Materials Testing

The SILVRCLAW rim is comprised of load-carrying fiber layers that are alternated with binding thermoplastic membrane layers. Once cooled from an application of heat, administered through the use of embedded heater wires sewn into a portion of the fiber layers, the SILVRCLAW rim rigidizes and is capable of transferring external loads through its medium and into the spoke system, while simultaneously minimizing local bending and buckling due predominantly to local cleat loads. In order to verify the overall SILVRCLAW material deployment concept in Mars conditions, coupon level testing was conducted emulating Mars thermal boundary conditions and differential atmospheric pressure (Fig. 9). Post deployment strength was determined through 3 point bending tests.

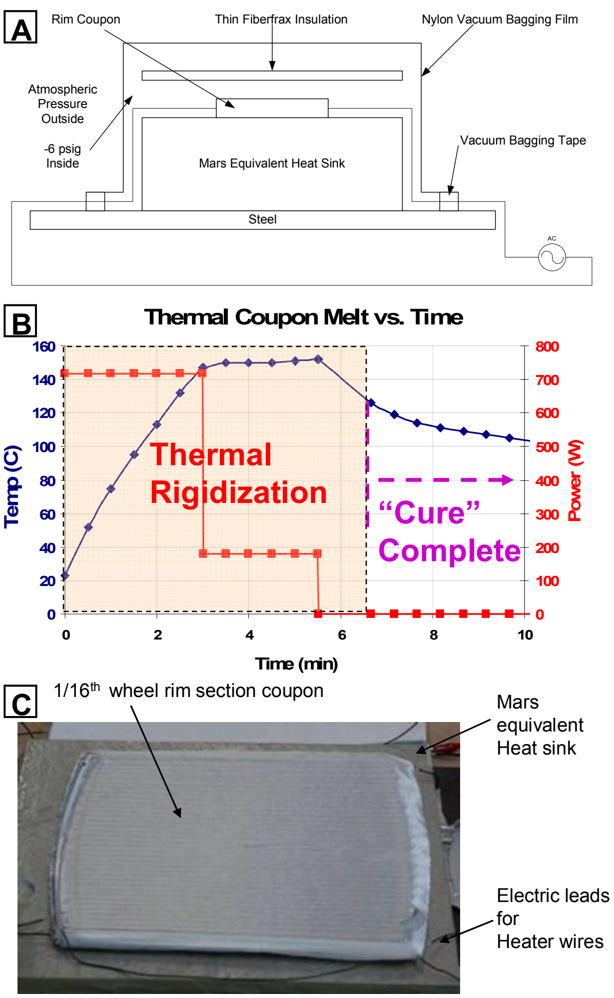

Figure 9 – 1/16 scale SILVRCLAW exoskeleton deployment test. A) Experimental setup; B) Temperature and power profiles during coupon test deployment; C) Material post-deployment

Prior to conducting the deployment experiments a best case theoretical energy requirement per rim area was derived based on known material chemistry. The actual energy used was found by integrating the voltage times amperage of the heater system over the thermal deployment time. Heating efficiency as a function of applied power and material lay-up was determined by comparing the actual heat input to the theoretical value (Table 5). Figure 10 illustrates the three point bending tests on the thermal coupons from Table 3 as well as two additional coupons. Based on these tests, keeping melt times as low as possible ensured that environmental losses were kept to a minimum. Experimental test results indicate that a single heater wire layer would be sufficient for material rigidization, but the use of two layers adds an additional level of system redundancy.

Table 5. Summary of thermal coupon tests

Thermal Coupon Summary					
Test	**Ideal Energy/ Unit Area (Whr/m^2)**	**Actual Energy/ Unit Area (Whr/m^2)**	**Time (min)**	**Power/ Unit Area (kW/m^2)**	**Efficiency (%)**
1	477	715	10	4.3	67%
2	467	1441	30	2.9	32%
3	318	692	20	2.1	46%
4	382	604	12	3.0	63%

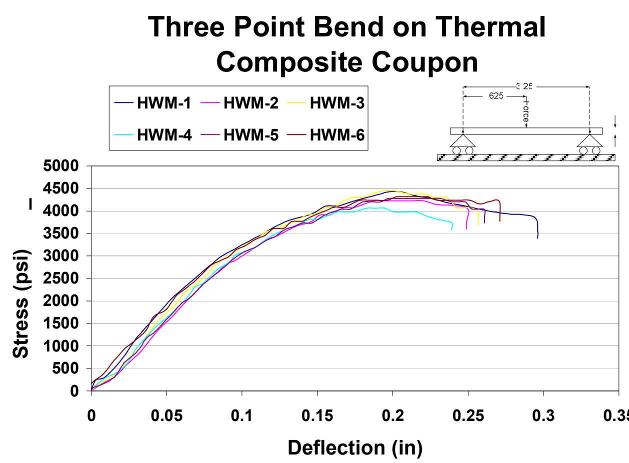

Figure 10 – Three point bending test results (HWM's) of deployed thermal coupons. Coupons were statistically tested in bending to determine what, if any, effect deployment powers had on rim material strength.

Spoke System

The SILVRCLAW spoke system maintains a pre-strained structure and allows large torsional loads to be transferred between the wheel rim and hub. Long term (>3 month) testing of the first iteration of spokes indicated that the bonded interface at the hub was prone to creep. In order to eliminate this creep a tension insert was incorporated into the spoke system design. Follow-on long term testing has indicated that this insert has eliminated creep at this interface. During the spoke manufacturing process, an additional 8% of the total number of manufactured spokes were sampled to failure. Based on this sampled data set, the manufactured spoke strength varied by < 2.6% in strength and < 5.2% in spring constant. The spoke system interfaces to the rim harness through stress-attenuating tabs as shown in Fig. 11.

Figure 11 – Rim-to-Spoke Interface

Inflation System

The inflation system fulfills two major roles on the deployable SILVRCLAW wheel. First, it is responsible for creating and maintaining the proper geometric shape throughout the entire deployment process, and second it is responsible for applying the correct pre-strain to the spoke system, which subsequently transfers a portion of the pre-strain load to the exoskeleton rim after rim thermal deployment. For the bag geometry shown in Fig. 1, the efficiency of bag pressure in stretching spokes is calculated to be 67% (compared to an ideal pressure vector field aligned to the spokes with no pressure-membrane applied counter-loads) based on the geometry and free body diagrams of the stressed (and expanded) membranes and interface spoke angles. For a spoke pre-strain value of 0.5%, the corresponding bag pressure is estimated to be 41.3 kPa (6 psi). This assumes linear expansion in bag geometry.

Multiple revisions of the inflation bag have been considered, fabricated, and tested prior to downselecting to the current geometry shown in Figures 1&12. Once the bag and seam designs were found to be adequate for supporting membrane loads, a simple experiment was conducted that plotted expected bag expansion as a function of bag pressure. The results of this experiment were used to estimate the appropriate individual shell starting dimensions (Fig. 1) that would ensure that the entire bag closely conformed to the final desired wheel geometry under peak bag pressure and strained spoke load. With the inflation bag and spoke harness assembled it was possible to verify the inflation bags ability to pre-strain the entire spoke system. Verification of this was done by directly measuring the strain in a random sample of spokes. At the conclusion of this testing it was determined that the inflation system was performing better than expected, only requiring 34.5 kPa (5 psi) of bag pressure to achieve the proper 0.5% pre-strain. This discrepancy appears to be due to the nonlinear growth in bag expansion vs. bag pressure, use of worst case spoke spring constants, and a conservatively estimated bag efficiency.

The current inflation bag design accommodates a very large factor of safety relative to the required maximum inflation pressure. This is done in order to assure the safety of those around the structure during its testing phase. Future designs can be optimized to reduce the factor of safety and likely decrease the overall inflation bag mass by >2.

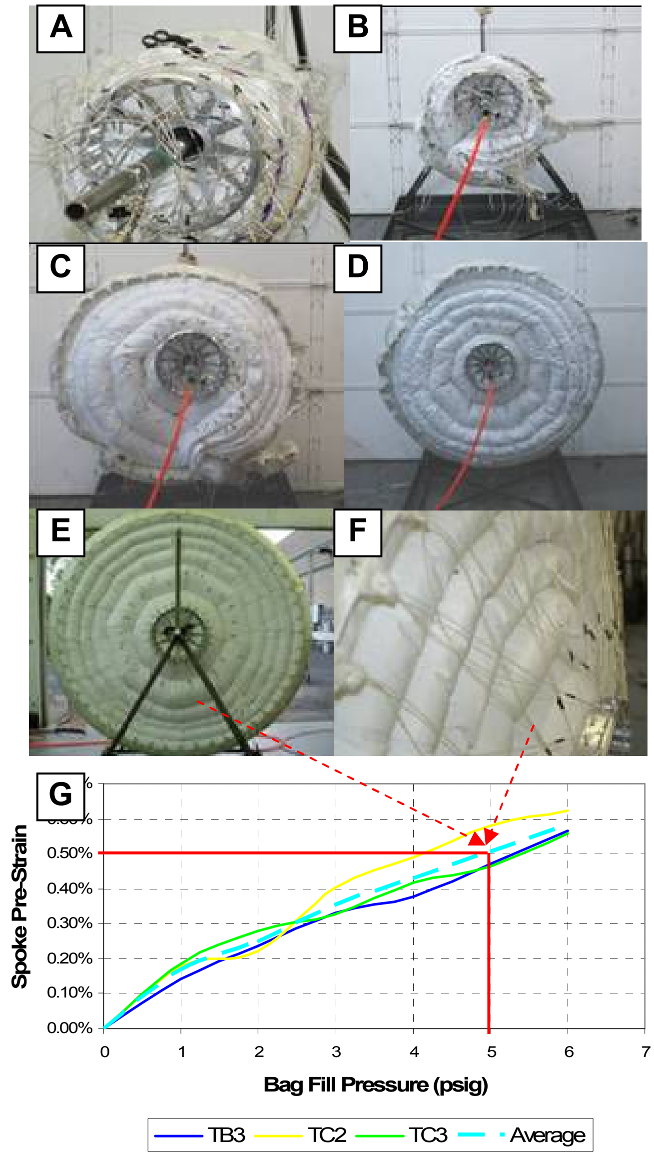

Figure 12 – Prototype SILVRCLAW inflationary deployment. A) – F) Incremental deployment steps during inflation; G) Sampled spoke strain (3 spokes at 120° degree) vs. bag fill pressure.

Initial SILVRCLAW Deployment Prototype

Initial deployment experimentation saw the complete integration of all SILVRCLAW sub assemblies; hub system, inflation system, heater layer system, and spoke/ spoke harness system. The inflation system was pressurized to provide the correct deployment geometry and the heater layers were connected to an AC power supply. During the testing the amperage of the layer circuits were measured and the temperature of the rim was monitored through the use of four thermo-couples that spanned radially across the rim, allowing for an accurate picture of the temperature gradient present across the rim. These temperatures were measured throughout the entire duration of the test including the cool down period after melt temperatures were reached throughout the entire rim.

At the conclusion of testing it was found that the heater wires within the heater layers were sufficient to provide the rigidization melt power needed. While the edges of the rim exhibited poor wetting, due to the loss of the heater circuit nearest the edges, the interior portions showed excellent wetting that lead to a full rigidize rim capable of transferring loads to the fibrous spoke system. (Fig. 14) To date there has not been any objective load carrying capability testing done, but subjective testing has shown the rim is capable of supporting small loads, such as a person leaning on the top portion of the rim. Future testing would allow for the complete objective testing of the load carrying capabilities of the deployed rim.

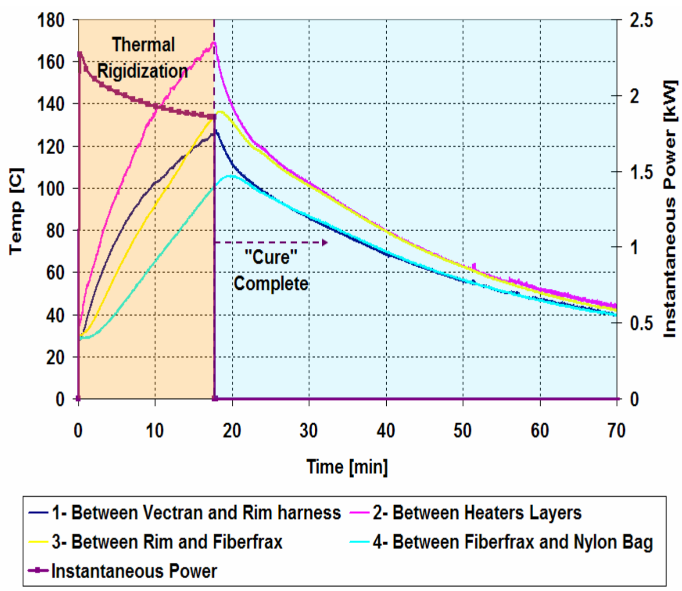

Figure 13 – Temperature and rigidization power profiles for the complete SILVRCLAW rim during deployment testing. Series 1 – 4 span radially from outer most, Vectran layer, to between the inflation bag and the insulation protecting it from the deployment heat.

Figure 14 – Shown leaning against a standard sized automobile, the relative size of the initial SILVRCLAW deployment prototype is apparent. The nominally attached inflation bag is deflated and pulled away from the rim in order to show the fibrous load carry spokes and rim rigidity.

An initial estimate of the deployable wheel mass is provided in Table 6. The inflation system and hub system are both suboptimal designs that were intended as proof concept systems. Future iteration may see significant mass reductions in both of these systems leading to a decrease in total mass.

Table 6. Current SILVRCLAW system wheel mass

SILVRCLAW System Mass Breakdown			
Sub System	**Mass (kg)**	**% of Mass**	**Comments**
Rim	7.9	46.6%	Bases on densities and layering of individual constituents
Inflation Bag	3.4	20.3%	Estimated based on mass of shell 7 and relative surface area of individual shells
Hub	5.0	29.7%	Actual Measurement
Spokes	0.5	2.8%	Actual Measurement
Heater Wire	0.1	0.6%	Length estimate, gauge to be used, material density
Total	16.9		

5. Conclusions

This paper discusses the design, prototype construction and experimental verification of an innovative wheel for planetary rovers. Through a special deployment and rim rigidization process SILVRCLAW attains its functional geometry. Large SILVRCLAW wheels with 1.3 to 1.5-m diameters can, therefore, be deployed from a minimal stowed volume. Such large wheels would be capable of negotiating more than 80% of discrete rocks on the Martian surface, traverse across >1m gaps, and climb angle-of-repose slopes, all the while carrying up to 100's kg wheel loads in Mars gravity (many 100's of kg in lunar gravity) with minimal energy consumption.

From a robotic performance standpoint SILVRCLAW wheels replace computationally-expensive planning software and complicated obstacle detection sensors. A SILVRCLAW rover nominally drives over obstacles rather than navigate around them. This encourages simpler and therefore far more reliable Mars rover designs. Navigation can be conducted using orbital imaging high resolution data sets. Furthermore, as more aggressive lunar and Mars terrains are imaged from orbit, it is likely that current mobility systems will require significantly enhanced mobility than is currently available in order to physically navigate in the terrains.

Preliminary experimentation has proven the viability of the SILVRCLAW concept and has yielded promising results on in-soil and extreme obstacle mobility performance (both positive and negative obstacles), energy efficiency, wheel loading, and endurance. Our next steps include more experimental measurements on loading and possible failure modes.

Future Work

Potential future activities for the SILVRCLAW concept may include:

- Investigation of varying wheel sizes.
- Testing of the SILVRCLAW deployment prototype in Mars terrain simulant test bed.
- Examination of side loading stresses in the rim and their effect on the spoke subsystem.
- Measurement of spoke stresses during traverses.
- Effects of different outer layer wheel coverings on wear and abrasion resistance.
- Investigation of preliminary rover designs.

6. ACKNOWLEDGEMENTS

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[5] Personal Conversation with Mr. Greg Peters, Extraterrestrial Materials Laboratory Lead Engineer, JPL.

8. BIOGRAPHY

***Mr. Christopher Mungas** has a B.S. in both Aeronautical and Mechanical Engineering (2005) from the University California, Davis. Following graduation, Christopher began working at Firestar Engineering where he has participated in the development and design of the Nitrous Oxide Fuel Blend Optimized Breakdown System (NOFBOBS); Rigidizable Inflatable Deployable Dwelling (RIDD); and has been the lead developer and project manager of the Stowable, Large, Inflatable, Vectran, Rigidizable, Cold-resistant, Lightweight, All-terrain Wheel (SILVRCLAW) project. Christopher has had first hand involvement in the development of high pressure inflation bagging which conforms to specific geometries, embedded heater wire assemblies, and mechanical interfacing of rigid structures and Vectran/polyethylene composites. Christopher has also provided the day to day management of the SILVRCLAW project, which has included establishing and maintaining relationships with vendors, preparation of monthly and quarterly JPL management reviews, and project liaison between Firestar and ProtoInnovations Management.*

Mr. Greg Mungas *currently works for the Jet Propulsion Laboratory (JPL) in the Life Detection and Sample Handling Technologies Group having recently transferred from JPL's Mars Mission Architecture and Advanced Studies group as an advanced studies lead and proposal manager. Mr. Mungas is the instrument technical lead and systems engineer for the Raman/CHAMP instrument at JPL. He also currently is a Principle Investigator and principal inventor of SILVRCLAW (an inflatable, rigidizable, large diameter rover wheel for extreme terrain navigation); a Principle Investigator and principal inventor (two patents pending) of NOFB monopropellant and rocket engine technology (a non-toxic, 300+s Isp, low temperature, self-pressurizing monopropellant alternative to hydrazine rocket technology) funded under the Mars Advanced Technology program; an Institutional Principle Investigator on a micro-LIBS/Raman ASTID (Astrobiology Science, Technology, and Instrument Development) award with Dr. Chris Dreyer at the Colorado School of Mines; an Institutional Principle Investigator and principal inventor of Pulsed Cavity Ringdown Laser Absorption Spectroscopy in a Hollow Waveguide funded under a NASA ASTID award in partnership with Dr. Chris Dreyer; and a Co-investigator on "Processing Icy Soils" funded under JPL's internal Research and Technology Development (RTD) program. In 2002, Mr. Mungas founded with partners, Firestar Engineering, LLC to support the HOMER Mars Scout mission proposal. Mr. Mungas was the proposal manager for a joint SETI Institute/Boeing and industry partners team. For recognition of work related to Firestar Engineering, LLC, Mr. Mungas was recently awarded a US Congressional Medal of Distinction for Businessman of the Year.*

Dr. Dimitrios Apostolopoulos *is a Senior Systems Scientist at the Robotics Institute of Carnegie Mellon University, Pittsburgh, PA, and a Chief Scientist at ProtoInnovations, LLC. His work focuses on robotics for discovery and exploration, and as a workforce in extreme applications and for hazardous duty on Earth and beyond. In the last 10 years Dr. Apostolopoulos has led high-profile robotics programs for space, defense, and private industry applications. Significant accomplishments of his work include the creation, development, and successful validation of robots for autonomous search of Antarctic meteorites, robots for long-range missions in polar environments, robust unmanned ground vehicles for USMC combat missions, hopping robots for all-terrain mobility, and reconfigurable and inflatable robotic locomotion systems for Mars exploration. His areas of expertise include robot design, robotic mobility, mechatronics, mechanisms, analysis, and control. Dr. Apostolopoulos holds a Ph.D. in Robotics from Carnegie Mellon.*

Mr. Michael Wagner *is a Commercialization Specialist at the National Robotics Engineering Center of Robotics Institute at Carnegie Mellon University, Pittsburgh, PA, and a lead researcher at ProtoInnovations, LLC. He has eight years of experience designing, building and deploying autonomous field robotics. He has led software development efforts to create robots that discovered meteorites in Antarctica, reasoned about their own solar power while exploring Arctic landscapes, and found life in the barren, Mars-like Atacama Desert in Chile. He has also been lucky enough to travel around the world to field test these robots. At ProtoInnovations he is responsible for product design, software development and data analysis. Mr. Wagner received a B.S. and M.S. in Electrical and Computer Engineering from Carnegie Mellon University.*

Mr. David Fisher *graduated from the University of Colorado with a B.S. in Mechanical Engineering. While pursuing his B.S., David developed a shock-less disengaging satellite mount concept for Ball Aerospace. Following graduation he began work with Firestar Engineering where he has had significant involvement in two NASA Mars Technology Programs, NOFBOBS and SILVRCLAW; and has been a Principal Investigator on a NASA SBIR phase I project, RIDD. Prior to his work with RIDD, David was the day to day manager of SILVRCLAW, and in his current SILVRCLAW position provides ongoing engineering support. David also acts as the lead mechanical engineer for the development of a low cost, high performance monopropellant (NOFBOBS). In this role he has engineered, designed, and fabricated rocket thrusters, instrumentation, and testing hardware. Initial results of his engine development work have yielded successful runs of high ISP performance micro-thrusters.*